# DEVELOPMENT STUDY OF PENNING ION SOURCE FOR COMPACT 9 MeV CYCLOTRON*

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*Abstract*

Penning Ion Gauge (PIG) source has been used in internal source for cyclotron. The PIG source produces $H^-$ ions. This source consists of cold cathode which discharges electrons for producing $H^-$ ions and anode for making plasma wall. Tantalum which is cold cathode was used for emitting electrons and tungsten copper alloy was used for anode. Optimization of cathode and anode location and sizing were needed for simplifying this source for reducing the size of compact cyclotron. Transportation of electrons and number of secondary electrons has been calculated by CST particle studio. Calculation of PIG source in 9 MeV cyclotron has been performed by using various anodes with different size of expansion gap between the plasma boundary and the anode wall. In this paper design process and experiment result is reported.

## INTRODUCTION

The compact 9 MeV cyclotron which is constructed in Sungkyunkwan University accelerates the $H^-$ ions in order to extract proton beams. The negative ions are stripped by carbon stripper. The internal PIG source is widely used for producing and accelerating $H^-$ ions. The cold cathode type PIG source consists of a hollow anode cylinder with two cathodes on each end. Electrons emitted from two cathodes collide with $H_2$ gas for making plasma.

The electron collision processes such as dissociative electron attachment and polar dissociation with neutral molecules are the responsible of production of $H^-$ ions in the low density plasma [1, 2] . The size of PIG source is related with transition region of this low density plasma.

In the compact 9 MeV cyclotron, the magnetic field of the cyclotron center is 1.366 T and the pole gap of magnet is 60 mm. The hollow anode cylinder's length and the position of cold cathodes should be in this space. The calculations of the length of transition region, transportation of electrons and number of secondary electrons are done by CST Particle Studio [3] for concluding the length of PIG source. The magnetic field of permanent magnet is calculated by TOSCA [4].

## DESIGN STUDY OF PENNING SOURCE

The Penning ion source (Fig. 1.) consists of a hollow anode cylinder with a cathode on each end. Electrons emitted from cathode move towards to the anode under electric field, while a homogeneous parallel magnetic field distributed between the two cathode electrodes confines the electrons inside the anode. This magnetic field also keeps the electrons oscillating between two cathodes to produce greater ionization efficiency.

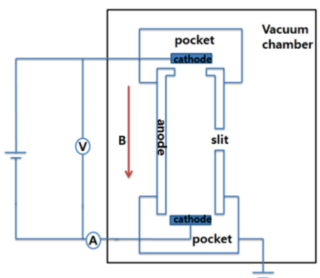


Figure 1: Schematic of the PIG ion source.

In the PIG ion source, the hydrogen plasma is weakly ionized. The length of transition region is related to the length of cathode to anode. In the transition region, electrons are collisional equilibrium and the charge neutrality is not preserved. The strong electric field from cathode penetrates in this region. We assume this situation in CST particle studio and simulate the trajectory of electrons and electric field.

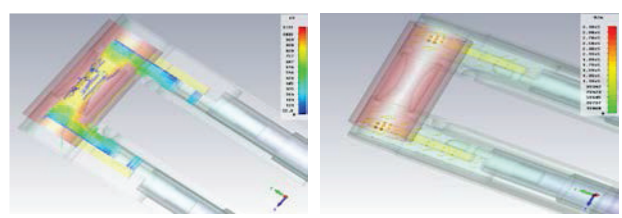

Figure 2: The electron trajectory and electric field of ion source.

For the weakly ionized plasma, we assume the fluid equation for calculating the length of transition region (see Eq. 2).

$$n_e = n_0 \exp(-\frac{eE}{T_e} x) \quad (1)$$

From the results of Chen's experiment [5], the ratio of the electron density $n_e$ and the charge density at the plasma edge $n_0$ (where x=the length of transition region) is 0.2. As the result of Eq. 1, we can get the electric field

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in the transition region.

$$E = 1.6\frac{T_e}{ex} \tag{2}$$

In the Eq. 2, $T_e$ is the average electron energy in the center of anode (=550eV) and electric field is 1490 V/cm from the simulation. As the result the length of transition region is 0.59 cm. With this result we assume the distance between two cathodes is 3.6 cm because the length of the anode, two cathode sheaths and the length of transition region (for two cathodes) should be the plasma height.

For the cathode material, tantalum is chosen because it is stable in operation and exhibits higher wear rate but lower arc current [6]. The tantalum is fabricated as 2 mm thickness and 8.6 mm diameter for covering plasma. They are possible to screw them into cathode support block which is applied high voltage and easily replaced and removed.

The shape of anode is decided by the simulation of number of secondary electrons in CST particle studio. The material of anode is tungsten-copper alloy (90% of tungsten and 10% of copper) by considering the material thermal properties. The anode length is 1.5 cm for covering two transition regions and cathode sheaths.

The number of secondary electron is related with discharging in plasma. The electron density should be high for high efficient ionization that many electron-neutral collisions happen.

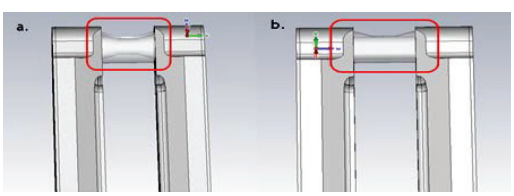


Figure 3: The optimization of anode shape.

Both of anodes are simulated in same internal diameter 6.5 mm by varying cathode voltage. The tapered anode has three times more secondary electrons than cylindrical one even if it has small space for plasma.

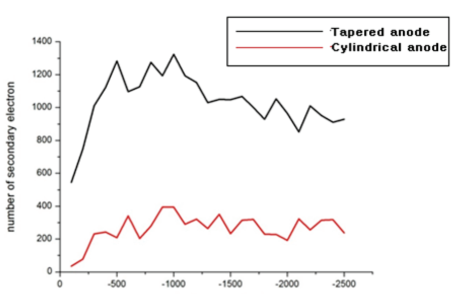


Figure 4: The number of secondary electron in two types of anode.

The tapered anode has better electric field for extraction of $H^-$ ions because tapered geometry has axial electric field which is extraction direction of $H^-$ ions.

The number of secondary electron in tapered anode is simulated by varying diameter from 5 to 9 mm. The 7 mm diameter of anode has the most number of secondary electron relatively.

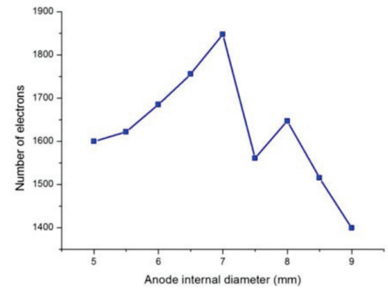


Figure 5: The number of secondary electron in tapered anode by varying diameter.

With simulated results, the PIG ion source is designed with CATIA P3 v5 r18 [6] and AutoCAD [7]. The total height of PIG ion source is 5 mm and the length of it is 650 mm. It is adoptable for the compact 9 MeV cyclotron magnet gap. The distance between cathode and anode is 0.68 cm and anode length is 1.5 cm. For covering two cathodes, two copper pipes and anode the copper block is designed. The hydrogen gas is inserted to this area.

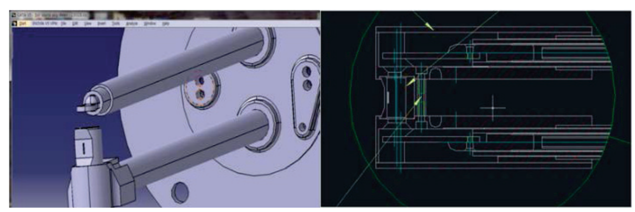

Figure 6: The design of PIG ion source.

The PIG ion source consists with austenitic stainless steel support pipes, oxygen free high conductive copper pipes, quartz, cathodes and anode. The material of stainless steel is SUS 304 which is not under the influence of magnetic field. Copper pipes are used for cooling the ion source and also applied high voltage due to quartz which electrically insulates the cathode and anode. The quartz is separate the stainless steel support pipes and copper pipes because the stainless steel pipes are contacted with anode and the copper pipes are attached with cathodes.

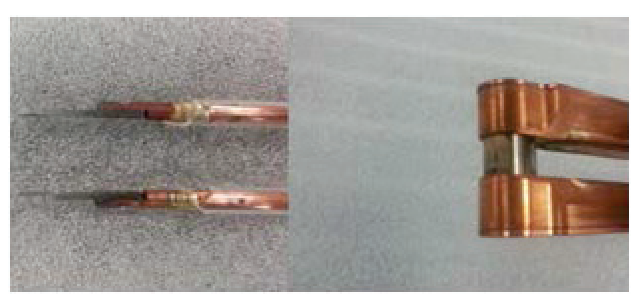

Figure 7: The manufactured PIG ion source.

## EXPERIMENTAL SETUP

The magnetic field is needed for keeping the electrons oscillating and confining them in the plasma. The permanent magnet 'vacodym 863 tp' is used for simulation in TOSCA [8]. The surface magnetic field of this permanent magnet is 2 T. The distribution of magnetic field in the center of PIG ion source is 0.4 T which is homogeneous parallel about 8 mm diameter.

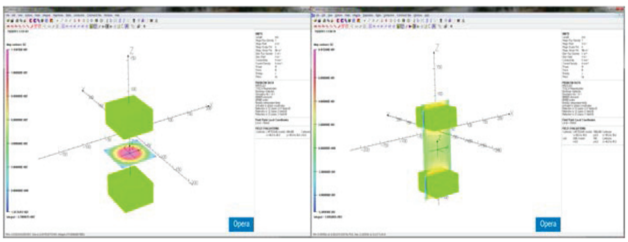

Figure 8: The magnetic field distribution in the PIG ion source.

Four permanent magnets are used for large homogenous parallel magnetic field. The distance between magnets is 9 cm. Separation of these four magnet design is illustrated in Fig. 9.

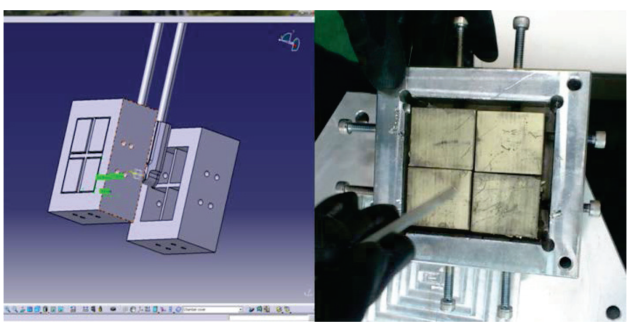

Figure 9: The four permanent magnet for distribution of magnetic field.

The test vacuum chamber [9] contains the whole PIG ion source. Same as the vacuum chamber used for a cyclotron system, this leak-proof vacuum chamber is illustrated in Fig. 10 is needed to prevent ions from colliding with air molecules during experiment. A circular shaped chamber with inner radius of 140mm was chosen. The vacuum chamber material should be non-magnetic, so material stainless steel 304 is used.

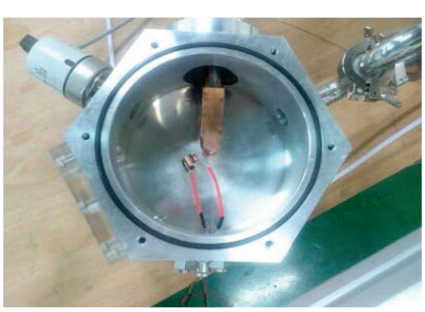

Figure 10: The vacuum chamber for testing PIG ion source.

Four parts attached to the vacuum chamber illustrated from Fig. 10: see through window, vacuum sensor gauge connected to vacuum pump system, vacuum system connection tubes, feed through connected to ampere meter and power supply which are used as simplified ion beam extraction system.

Oil rotary pump is used for low level vacuum pressure $10^{-3}$ mbar and turbo molecular pump is used for high level vacuum pressure $10^{-6}$ mbar. The pressure is $10^{-5}$ mbar level when the hydrogen gas is inserted in 3 to 5 SCCM.

A regulated power supply controls the output voltage and current to a certain value, despite the variations in either load current or the load voltage the controlled value is held as constant. Commercial power supplies are used in DC-operated ion sources. In order to protect the power supply device, resistors were connected in series to current-limit the discharge.

## CONCLUSION

Hydrogen plasma discharge is occurred when applied voltage is 1.8 kV. The applied voltage is dropped down to 0.6 kV and the arc current is possible to change 0 to 2A.

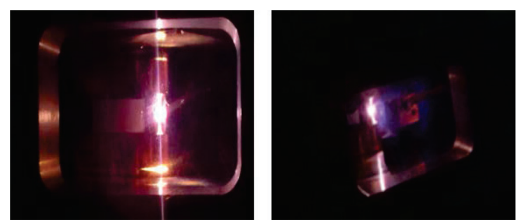

Figure 11: The plasma discharge in PIG ion source.

The extraction of $H^-$ ions is done by applying DC voltage to copper block. With this copper block the current of $H^-$ ions is measured. The current is 1 mA when the hydrogen gas flow rate is 3 SCCM and the applied voltage is 1 kV.

## ACKNOWLEDGMENT

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